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Prepared under

Contract No. Nonr-3815(00)(X)
Task NR 062-297

Supported jointly by
Department of Defense
Atomic Energy Commission
National Aeronautics and
Space Administration

Administered by

S. Doroff
Fluid Dynamics Branch
Office of Naval Research
Department of the Navy

THE PROPAGATION OF DISTURBANCES IN THE INFINITELY WIDE FOIL BEARING

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RR 67-13 May, 1967

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RESEARCH AND ENGINEERING PUBLICATION

ACKNOWLEDGEMENT

Thanks are due to Mr. E.J. Barlow for contributing to the simplified technique of sparse matrix solution used in this work and to Miss T. Woo for assistance in programming.

ABSTRACT

A technique for the solution of time dependent foil bearing problems is presented in this report. Solutions obtained for typical disturbances which are introduced into the bearing, indicate that they are swept out at a speed of, essentially, U/2. The effects of higher foil stiffness on this phenomenon are found to be small.

LIST OF FIGURES

NOMENCLATURE

A	Height of disturbance
a	Half width of square wavelet
D	Flexural rigidity of foil per unit width $D = \frac{Et^3}{12(1-\upsilon^2)}$
E	Modulus of elasticity
h	Film thickness
H	Dimensionless film thickness $\frac{h}{r_o}\left(\frac{6\mu U}{T}\right)^{-2/3}$
H_c	Dimensionless clearance at symmetry point of disturbance
p	Pressure under foil
p_a	Ambient pressure
R	Local radius of curvature
r	Polar radial coordinate
r_o	Shaft radius
s	Distance along tape
t	Time; Foil thickness
S	Stiffness parameter $S = \frac{D\epsilon^{-2/3}}{Tr_o^2}$
T	Tension per unit width
U	Foil velocity
ϵ	Dimensionless parameter $\frac{6\mu U}{T}$
μ	Viscosity
υ	Poisson's Ratio
π	Dimensionless pressure $\frac{p - p_a}{T/r_o}$
τ	Dimensionless time $\tau = \frac{tU}{2r_o}\epsilon^{-1/3}$
θ	Polar angular coordinate
ξ	Dimensionless angular position $d\xi = d\theta \cdot \epsilon^{-1/3}$

1.0 INTRODUCTION

Foil bearings have attracted attention in recent years due to their use in the computer and tape recording industries as well as in special lubrication applications. Most of the previous foil bearing studies have been devoted to steady state problems. The unsteady problem of a foil moving along a flat, solid surface was considered by Eshel and Wildmann [1]. These authors found by a linearized treatment of the differential equations that small disturbances in the shape of a tape propagate at half the speed of the tape while decaying. They also concluded that large symmetrical disturbances do likewise. This report will investigate disturbances in a foil moving along a circular cylinder. In this case, numerical methods are employed for the solution of the nonlinear differential equations.

2.0 FORMULATION OF THE PROBLEM

Consider an infinitely wide, perfectly flexible, massless foil moving at a constant speed along a cylinder of radius r_o. The foil is under a tension T and sweeps with it a lubricating film of air which is considered incompressible. At time t = +0 a disturbance in the shape of the foil is introduced. The problem is to find the time history of the film thickness. The conditions under which the above simplifications are permissible were discussed in [1] and are satisfied in many applications.

The basic equations which describe the situation are given below.

The Reynolds equation describes the fluid flow

$$\frac{\partial}{\partial s}\left(h^3 \frac{\partial p}{\partial s}\right) = 6\mu U \frac{\partial h}{\partial s} + 12\mu \frac{\partial h}{\partial t} \tag{1}$$

The foil elastic behavior is described by

$$p - p_a = \frac{T}{R} - D\frac{d^2\left(\frac{1}{R}\right)}{ds^2} \tag{2}$$

where R is the local radius of curvature and D the flexural rigidity of the foil. In polar coordinates

$$\frac{1}{R} = \frac{\left[\left(\frac{dr}{d\theta}\right)^2 + r^2\right]^{3/2}}{2\left(\frac{dr}{d\theta}\right)^2 - r\frac{d^2r}{d\theta^2} + r^2} \tag{3}$$

$$r = r_0 + h \tag{4}$$

$$\frac{ds}{d\theta} = \left[\left(1 + \frac{h}{r_0}\right)^2 + \left(\frac{1}{r_0}\,\frac{dh}{d\theta}\right)^2\right]^{1/2} \tag{5}$$

The following dimensionless quantities are introduced:

$$\epsilon = \frac{6\mu U}{T} \tag{6}$$

$$S = \frac{D\epsilon^{-2/3}}{T r_0^2} \tag{7}$$

$$\Pi = \frac{p - p_a}{T/r_0} \tag{8}$$

$$H = \frac{h}{r_0}\,\epsilon^{-2/3} \tag{9}$$

$$d\xi = d\theta \cdot \epsilon^{-1/3} \tag{10}$$

$$\tau = \frac{tU}{2r_0}\,\epsilon^{-1/3} \tag{11}$$

By means of a perturbation process with $\epsilon \to 0$, used previously in Eqs. (1), (2) and (3), one may reduce the above equations to a first approximation:

$$\frac{\partial}{\partial \xi}\left(H^3 \frac{\partial^5 H}{\partial \xi^3} - H^3 \frac{\partial^3 H}{\partial \xi^3} - H\right) = \frac{\partial H}{\partial \tau} \tag{12}$$

The boundary conditions require that the foil will become asymptotically straight far from the spindle. To a degree of approximation consistent with the above, the boundary conditions become [2]:

$$H' \sim \xi \tag{13a}$$

$$H'' \sim 1 \tag{13b}$$

$$H^{IV} \to 0 \tag{13c}$$

as $\xi \to \pm\infty$

The initial film thickness distribution has to be prescribed:

$$H(\xi, \tau)\Big/_{\tau=0} = f_o(\xi) \tag{14}$$

In the specific cases investigated here, the steady state film thickness from Eqs. (2) and (3) was used. Specific disturbances were imposed on this clearance distribution. In the case of tension disturbance, the film thickness and angular coordinates were scaled by the tension ratio to the power 2/3 and 1/3, respectively, to accomodate for Eqs. (9) and (10).

3.0 SOLUTION

The problem which is of a parabolic type was solved numerically by the Lees implicit finite difference technique [4]. The essence of the method is as follows: Suppose the values of H at n points on a spatial grid at time τ are given. The values of H on the corresponding grid points at time $\tau + \Delta\tau$ are considered as n unknowns. If we approximate the lower order nonlinear terms of Eq. (12) by their known values at time τ, and use spatial central differences and backward time differences, we may replace the differential equation by a set of n-6 linear algebraic equations.

The boundary conditions, Eq. (13), are required to be exactly satisfied at some large finite values of $\pm\xi$ (points i = 1, n) thus yielding six additional equations. The resulting five-diagonal matrix equation was solved by an elimination procedure taking full advantage of the sparseness of the matrix. The technique used approximately 8 x n subtractions, 14 x n multiplications and divisions, and 6 x n storage locations.

4.0 RESULTS

The response of the foil bearing to some disturbances indicative of the general behavior is graphically presented in Figs. 1 to 6. The film thickness distributions at successive time intervals are shown by displacing the datum for two consecutive curves by one division. The clearance scale is marked for the initial film thickness distribution only. The dimensionless time τ is marked on each curve. The two vertical lines indicate the points of tangency.

Figures 1 and 2 show the response to a square wavelet. The effects of disturbance width 2a and height A are also shown. In the linearized case [1], a correlation on the basis of

$$\frac{H_c - H^*}{2A\sqrt{\pi}} = f\left(\frac{\tau^{1/4}}{a}\right) \qquad (15)$$

exists, where H_c denotes the film thickness at the symmetry point of the disturbance. The nonlinear effects are, somewhat surprisingly, not substantial. In Fig. 3 the response to a saw tooth wavelet is displayed. The prediction of [1] that disturbances propagate at U/2 except for a small initial time interval in the case of nonsymmetrical large disturbances, is verified in Fig. 4.

Figure 5a shows how excess fluid inserted into the bearing is being swept out with a front moving at U/2. Figure 5b demonstrates how additional fluid is pumped into the bearing in response to a sudden reduction in tension.

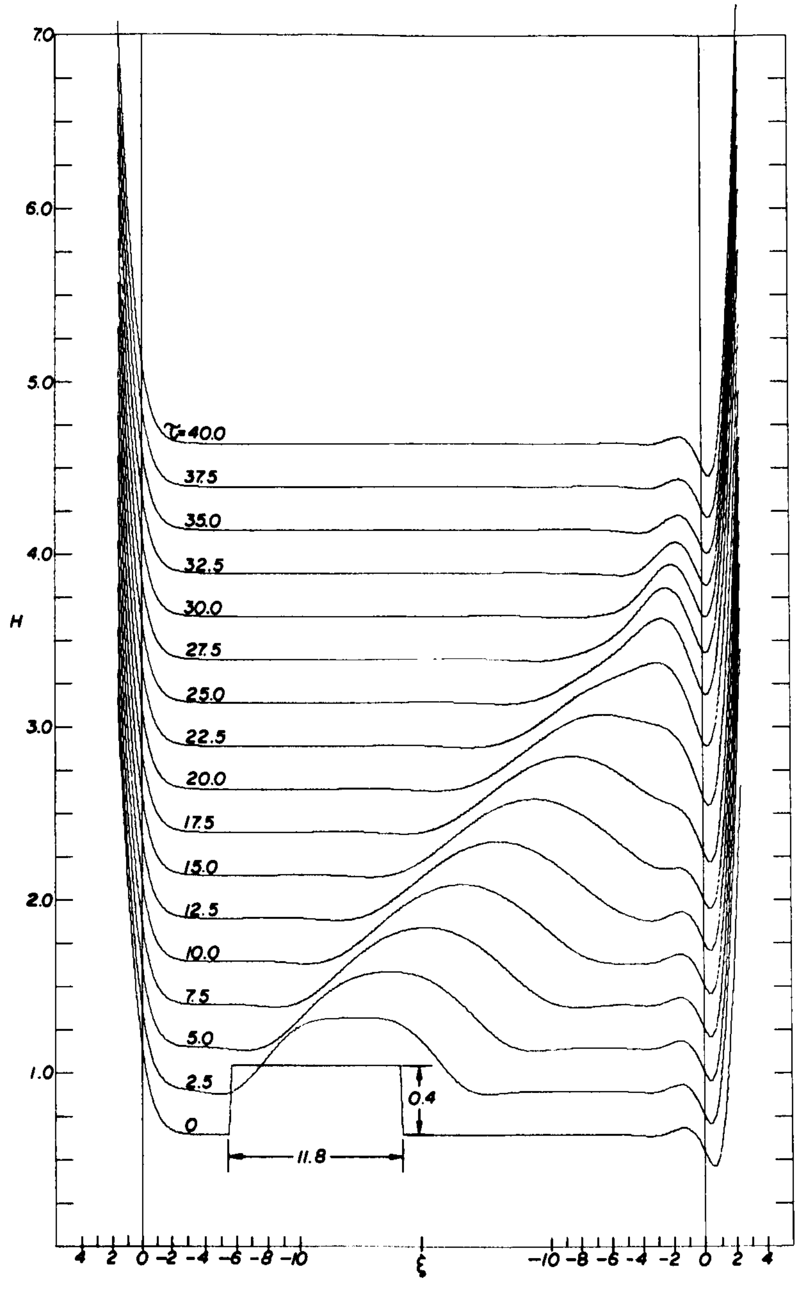

Fig. 1a Dynamic Response of a Foil Bearing to a Square Wavelet Disturbance in the Uniformity Region.

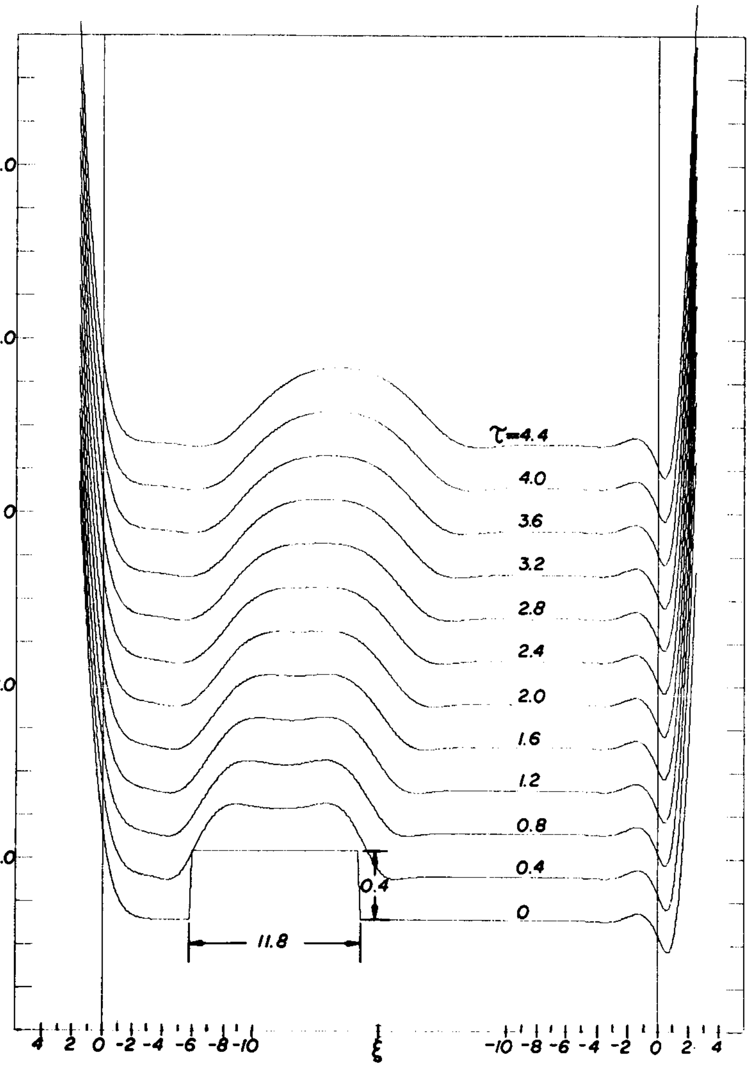

Fig. 1b Detailed Initial Response to a Square Wavelet Disturbance of Width 2a = 11.8 and Height A = 0.4

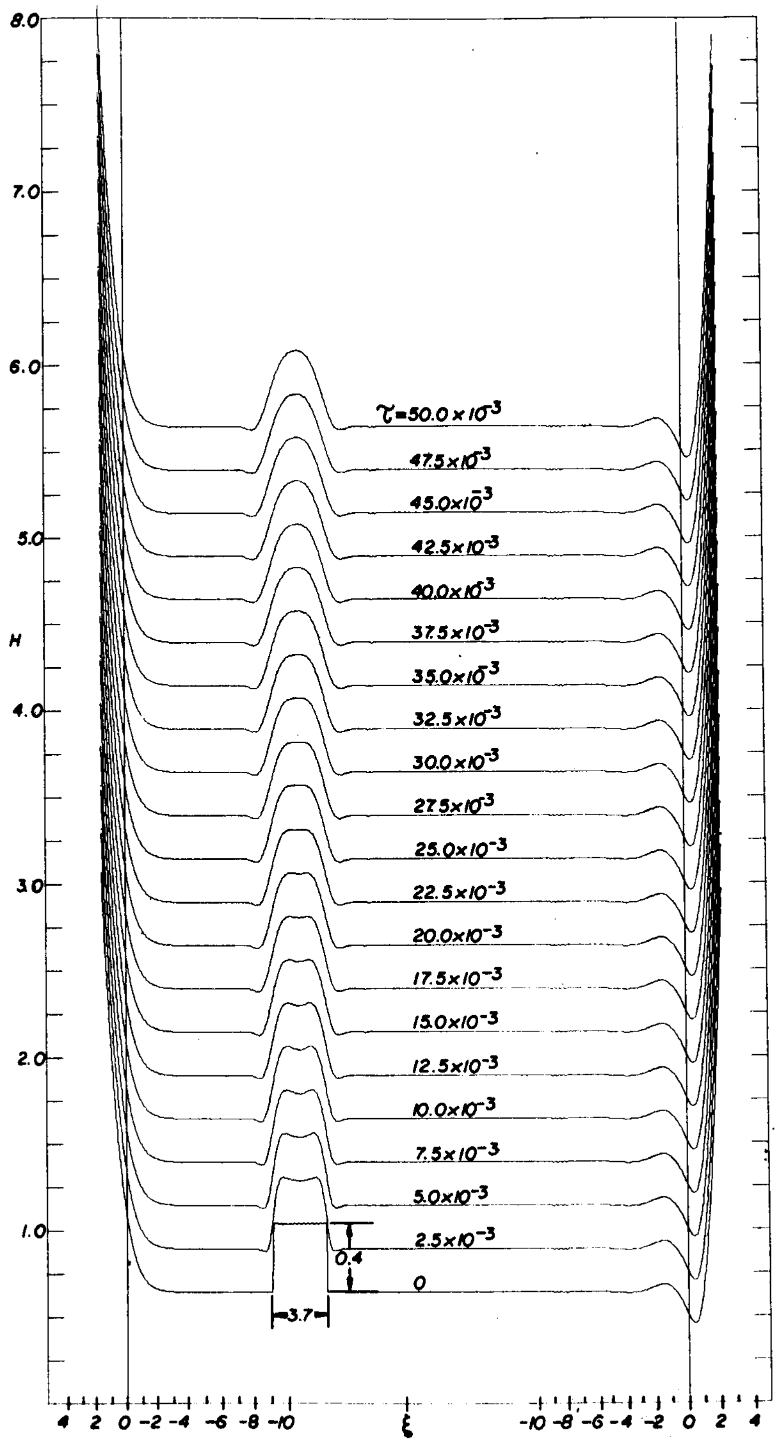

Fig. 1c Detailed Initial Response to a Square Wavelet Disturbance of Width $2a = 3.7$ and Height $A = 0.4$

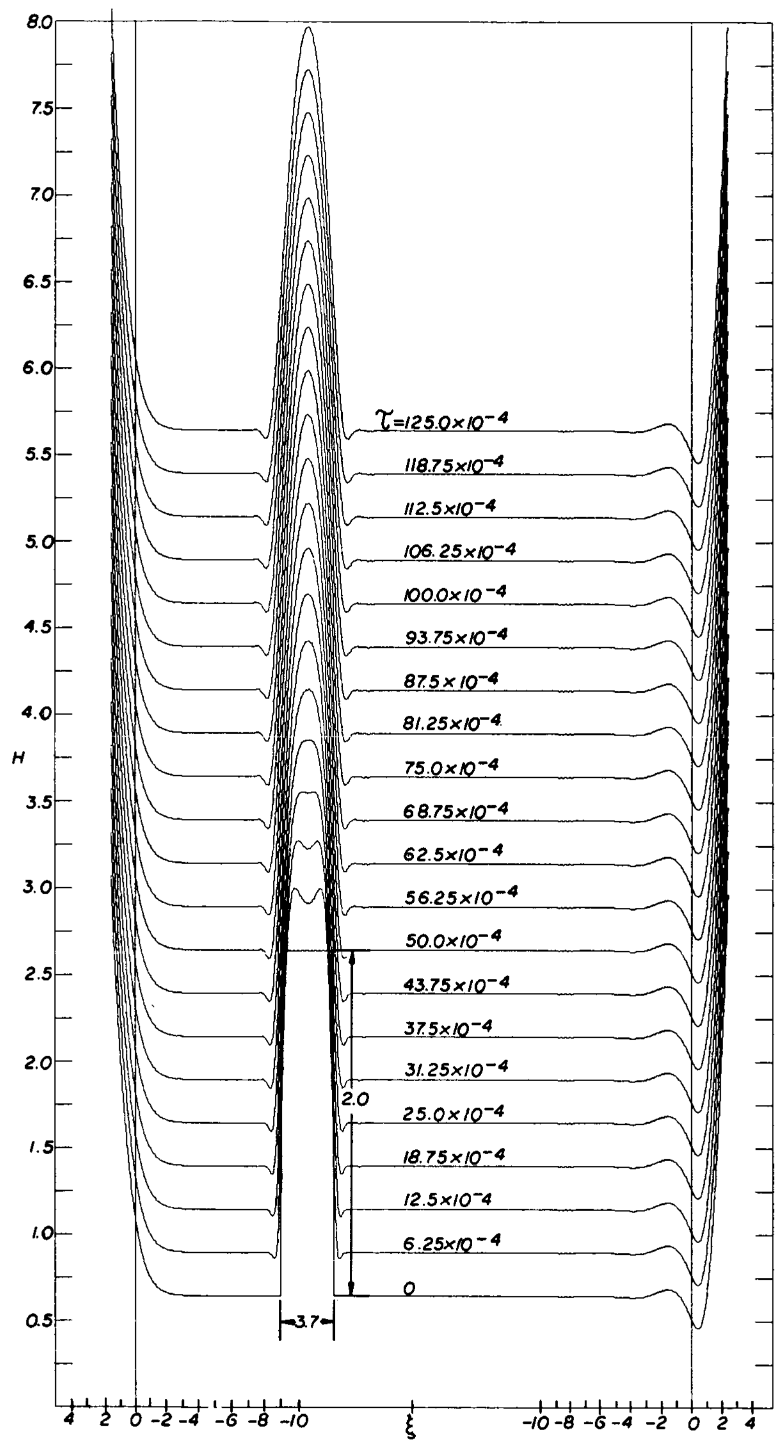

Fig. 1d Detailed Initial Response to a Square Wavelet Disturbance of Width 2a = 3.7 and Height A = 2.0

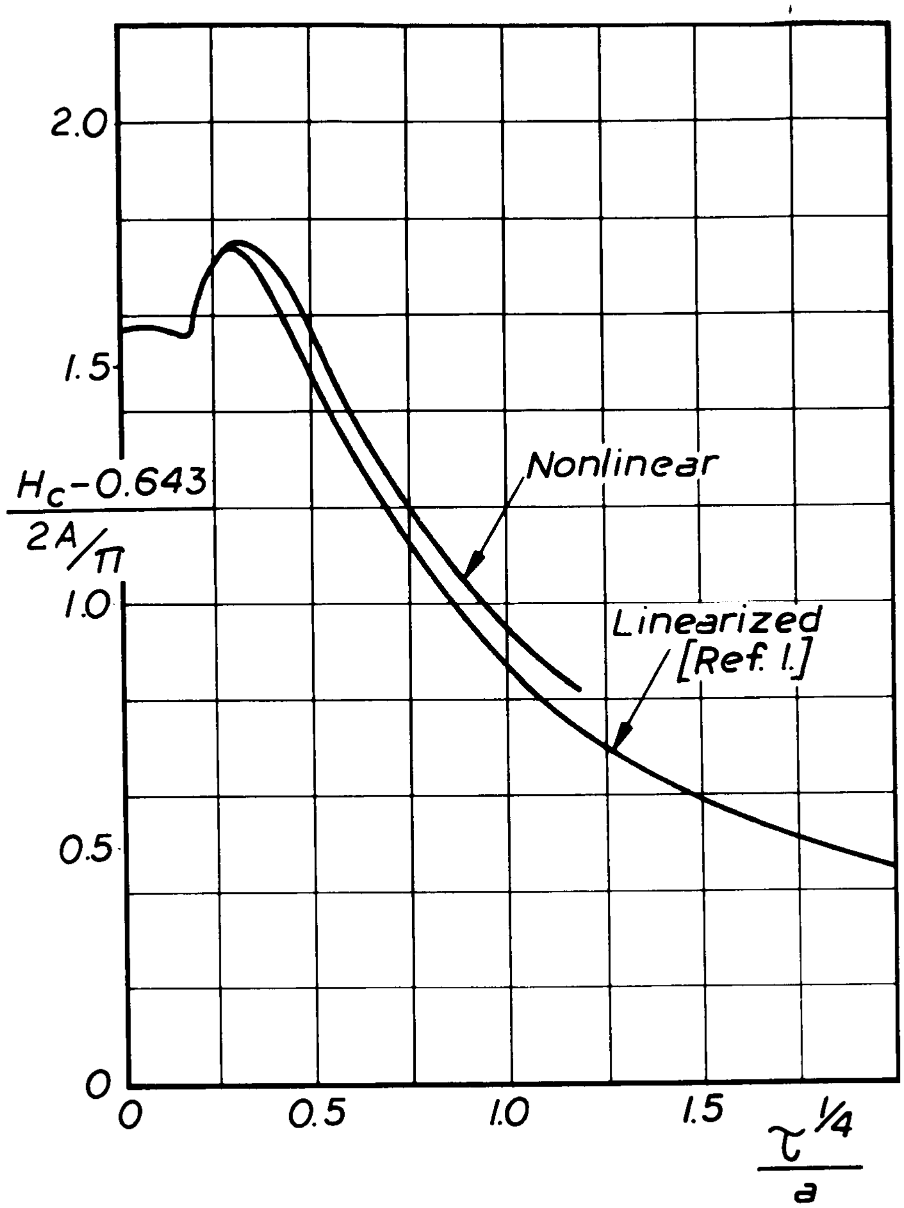

Fig. 2 Film Thickness at Symmetry Point of Square Wavelet Disturbance versus Time

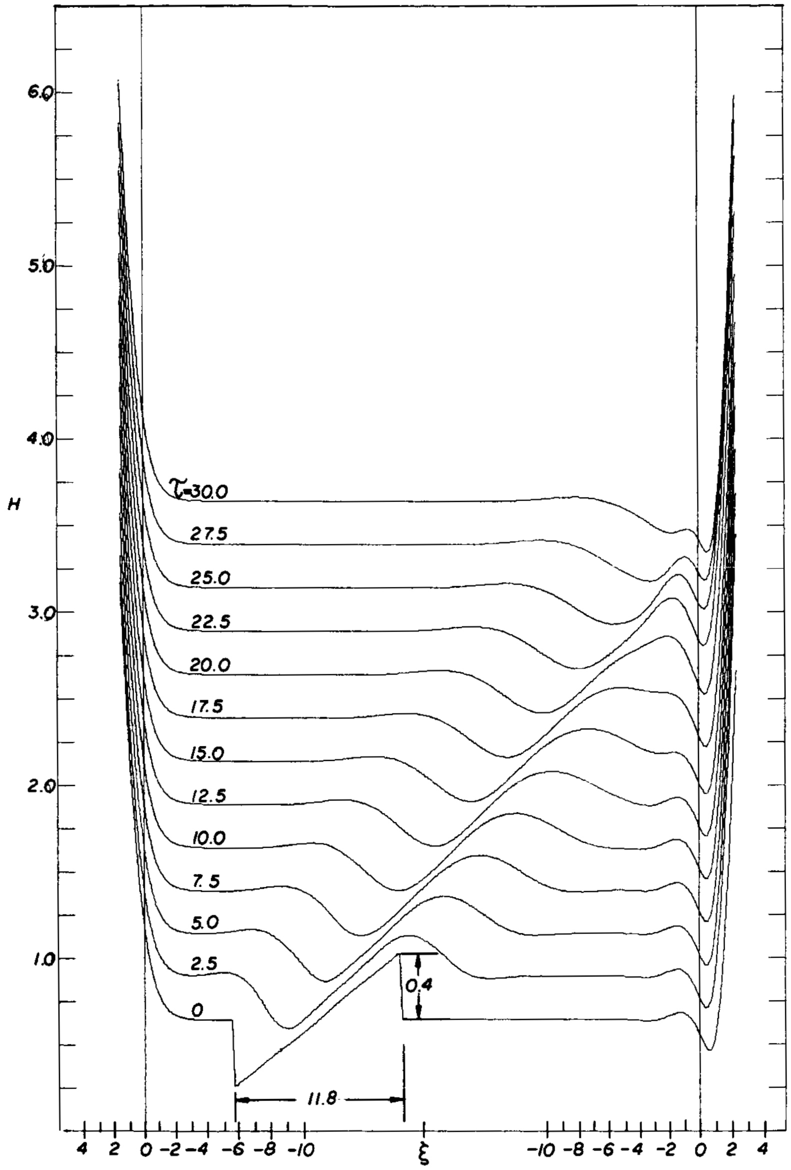

Fig. 3 Dynamic Response of a Foil Bearing to a Saw Tooth Wavelet of Width 2a = 11.8 and Height A = 0.4

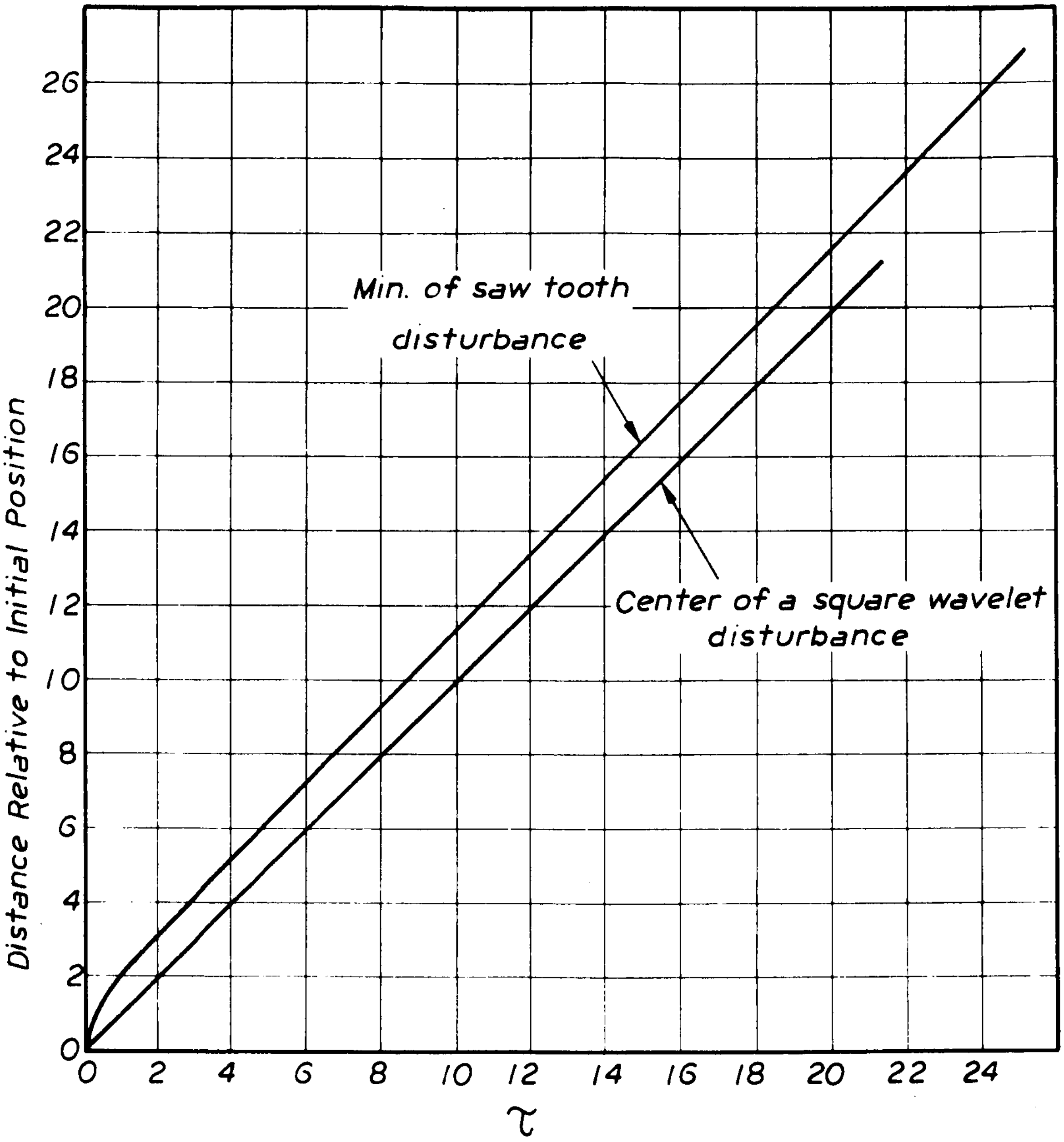

Fig. 4 Position of Symmetry Point and of Minimum Point for Square and Saw Tooth Wavelets Respectively

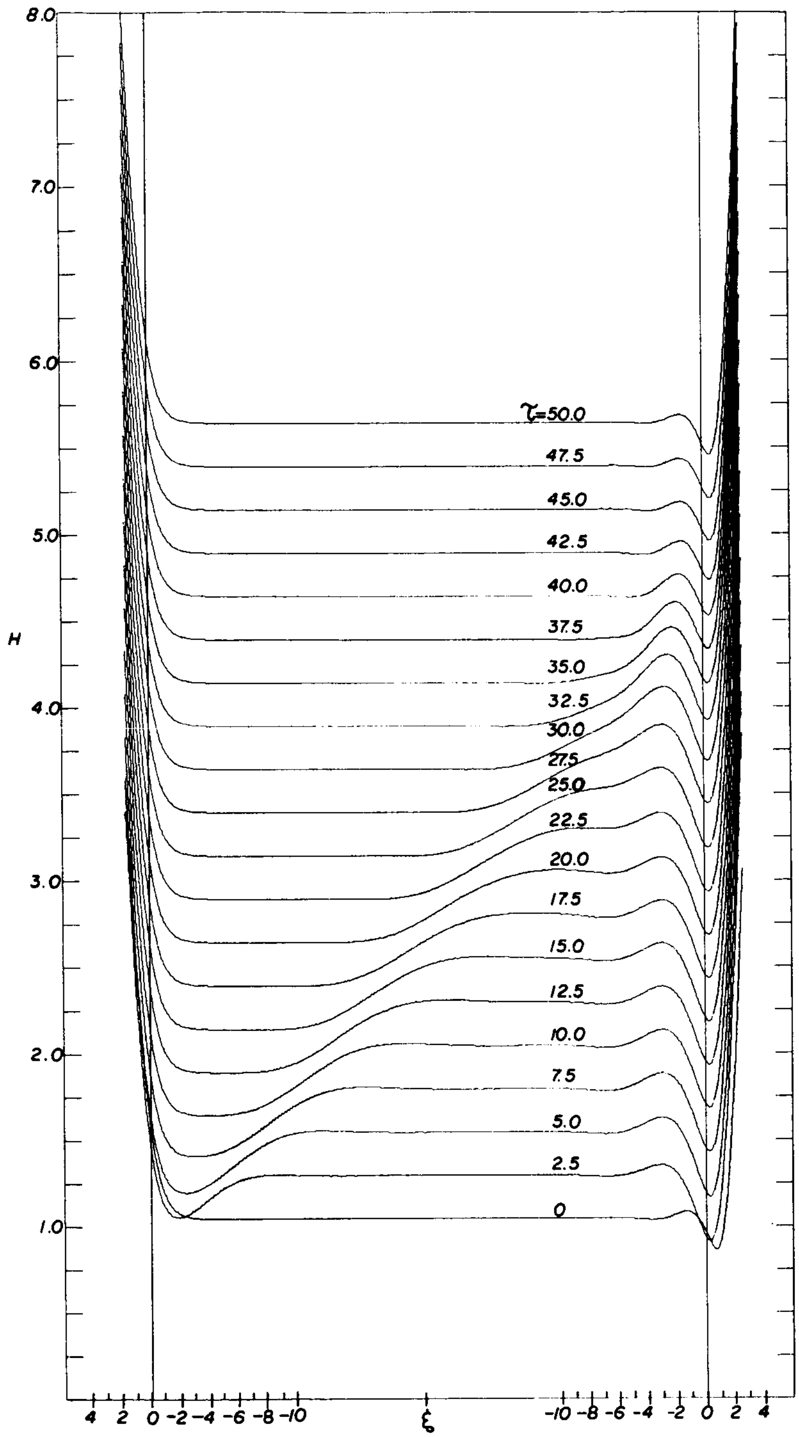

Fig. 5a Dynamic Response of a Foil Bearing to a Sudden Increase in Film Thickness

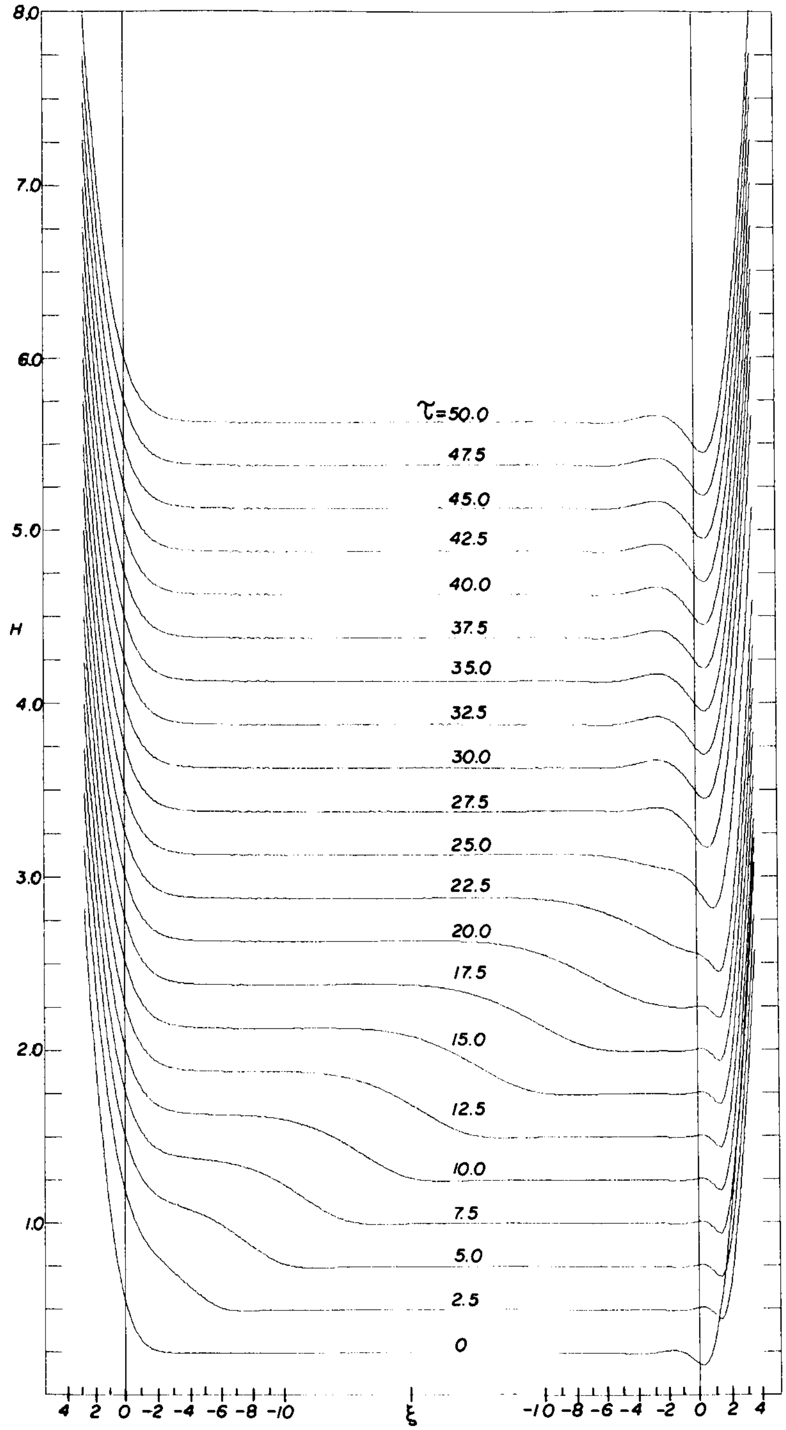

Fig. 5b Dynamic Response of a Foil Bearing to a Step Increase in Tension

In Fig. 6 the effect of foil stiffness is investigated. It is concluded that the speed of propagation of disturbances is insensitive to foil stiffness.

A mathematical explanation for this may lie in the fact that the higher derivatives in Eq. (12) are large only in the initial time interval while their effect subsides later and, hence, the disturbance propagates approximately as dictated by the equation

$$\frac{\partial H}{\partial \xi} = - \frac{\partial H}{\partial \tau} \tag{16}$$

with relatively slow decay rate.

A side result of the above calculations was the generation of steady state film thickness profiles as the asymptotic behavior of the unsteady film. This has been previously obtained in [3] by an essentially different technique and the results agree within 0.5 percent. In [3] the solution is based on integration of the ordinary differential equation representing the steady-state film thickness. The inlet and exit regions are solved separately and are linked by a central region of constant film thickness. Thus the angle of wrap is arbitrary as long as it is not too small, i.e. as long as no interaction between the exit and inlet region exists. Barlow [5] extended the solutions to small wrap angles. With the present technique the exit and inlet are solved simultaneously. This is particularly convenient for cases where interaction between the two regions exists.

In Fig. 6, the growth of amplitude and wavelength of undulations as a function of stiffness, mentioned previously in [3], may be observed. The larger the stiffness, the deeper will the inlet and exit undulations penetrate into the central region until they start to interact. Thus, large stiffness has an effect similar to that of a reduction in wrap angle.

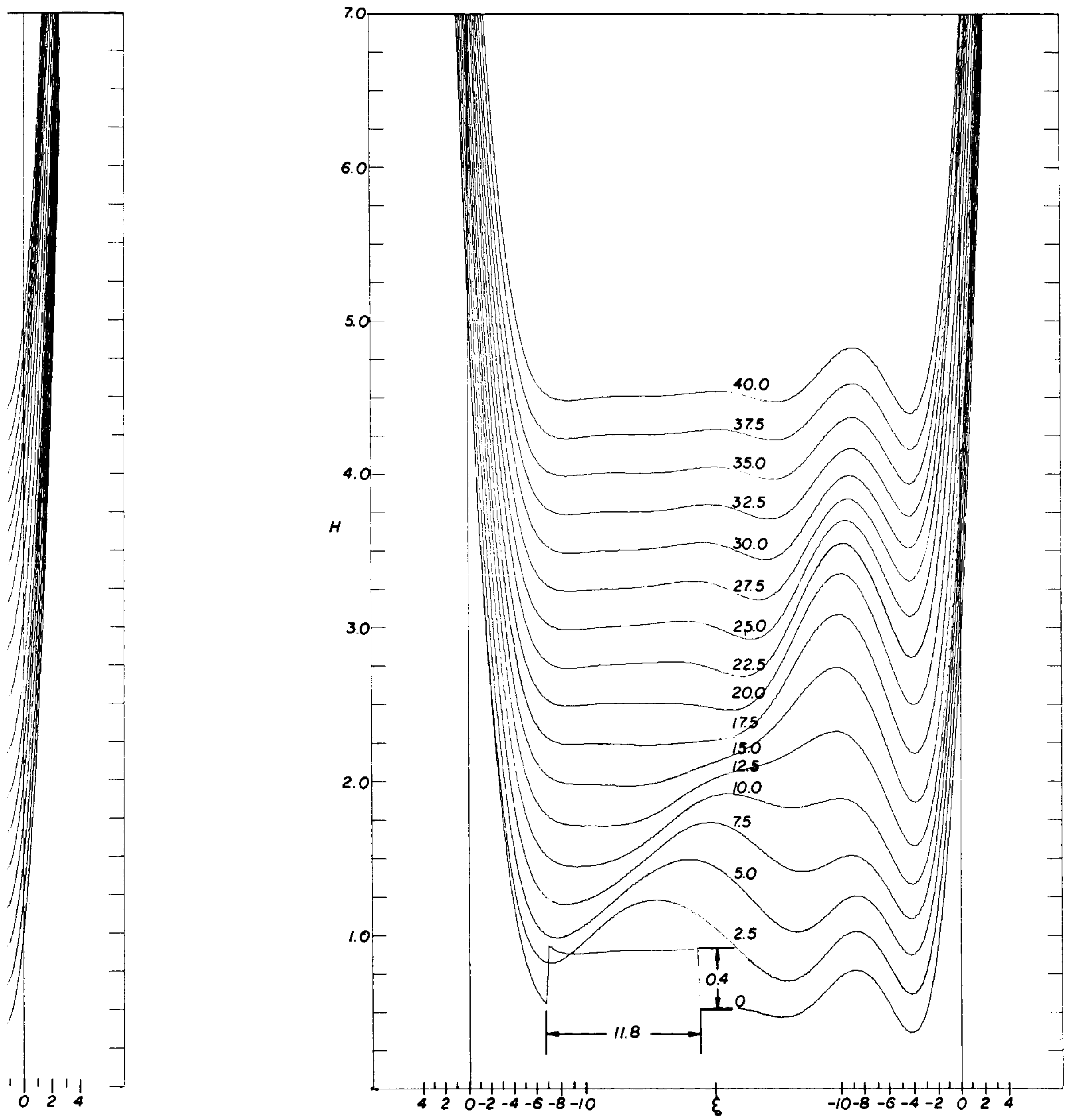

Fig. 6 Dynamic Response of a Foil Bearing to a Square Wavelet Disturbance for Various Foil Stiffness Values:

6a S = 0. 6b S = 10.
6c S = 50.

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Ampex Corporation 401 Broadway Redwood City, Calif.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

The Propagation of Disturbances in the Inifinitely Wide Foil Bearing

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Technical Report

5. AUTHOR(S) *(Last name, first name, initial)*

Eshel, A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
	36	5

8a. CONTRACT OR GRANT NO. Contract No. Nonr-3815(00)(X) b. PROJECT NO. Task NR 062-297 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) RR 67-13 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. AVAILABILITY/LIMITATION NOTICES

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11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Department of the Navy Office of Naval Research Washington, D.C. 20360

13. ABSTRACT

A technique for the solution of time dependent foil bearing problems is presented in this report. Solutions obtained for typical disturbances which are introduced into the bearing, indicate that they are swept out at a speed of, essentially, U/2. The effects of higher foil stiffness on this phenomenon are found to be small.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
FOIL BEARINGS FLUID MECHANICS REYNOLDS EQUATION FLUID FILMS MATHEMATICAL ANALYSIS WAVE PROPAGATION VIBRATING STRING						

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